

Model uncertainties in top-quark physics

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Abstract. The ATLAS and CMS collaborations at the Large Hadron Collider (LHC) are studying the top quark in pp collisions at $\sqrt{s} = 7$ and 8 TeV. Due to the large integrated luminosity, precision measurements of production cross-sections and properties are often limited by systematic uncertainties. An overview of the modeling uncertainties for simulated events is given in this report.

1. Introduction

The successful Run 1 of the LHC allowed the ATLAS [1] and CMS [2] collaborations to acquire pp collision datasets at $\sqrt{s} = 7$ and 8 TeV corresponding to 25 fb^{-1} . This lead to a reduction of the statistical uncertainties in top-quark measurements, especially in combined results [3, 4]. Among the systematic uncertainties, the ones on the modeling of top-quark pair and single-top events contribute significantly to the precision limit. Simulated events are predictions of the Standard Model of particle physics (or a theory beyond that) using Monte-Carlo (MC) methods, and consist out of matrix-element calculation, parton shower and hadronization stage, implemented in various publicly available codes [5–17]. These models are tuned to data from both current and preceding experiments. The resulting stable particles (photons, leptons, and hadrons) can be passed to a detector simulation in order to compare to data. This simulation chain allows for the determination of unobservable parameters (as the top-quark mass) or for the estimation of signal selection efficiencies, needed for cross-section measurements. This report discusses the most relevant uncertainties from perturbative QCD in Sec. 2 and those from soft QCD in Sec. 3, summarizing the prescriptions employed in ATLAS and CMS.

2. Perturbative QCD uncertainties

2.1. Parton density functions

The uncertainty on the parton density function of the proton is evaluated using the PDF4LHC prescription, creating an envelope of three PDF sets and their respective uncertainties [18]. Including a variation of the strong coupling α_s , a set of 147 PDFs is evaluated, becoming a bottle-neck for CPU-intensive analyses like matrix-element methods. Therefore, for insensitive analyses often only the variations of one PDF set are used and compared to the central values of the other PDFs. A prescription for covering all PDF sets and their uncertainties with a reduced number of variations would be desirable from experimental point of view, possibly in the framework of a meta-analysis [19].

ATLAS	PDF4LHC prescription, or uncertainties of default PDF + other central PDFs
CMS	PDF4LHC prescription, or uncertainties of default PDF

2.2. $t\bar{t}$ MC generator

The guidelines of the Top LHC working group [20] recommend the comparison of central predictions from different MC generators, using at least one multi-leg and one NLO generator setup. Additional uncertainties are estimated by parameter variations inside a generator framework to disentangle different effects.

ATLAS	Powheg+Pythia6 vs. MC@NLO+Herwig6 (vs. Alpgen+Herwig6)
CMS	MadGraph+Pythia6 vs. Powheg+Pythia6

2.3. Single-top MC generator

Simulating single-top t-channel events is possible in either the 5- or the 4-flavour scheme (FS). The 5FS is based on massless b quarks in the proton PDF, reducing the complexity of the LO calculation. The 4FS contains the $g \rightarrow b\bar{b}$ splitting, yielding a ME description of the additional b quark in the event. Matched schemes, as implemented in AcerMC and CompHep, combine the 5FS and 4FS LO diagrams, and NLO generators provide matching of diagrams in either 5FS or 4FS (Powheg, aMCatNLO).

ATLAS	AcerMC+Pythia6 (matched LO) vs. aMC@NLO+Herwig6 (4FS NLO)
CMS	Powheg vs. aMC@NLO (4FS NLO)

At NLO, single-top production in the tW channel overlaps with $t\bar{t}$ production. The diagram-removal scheme removes the double-resonant diagrams from the signal definition, while the diagram-subtraction scheme implements a subtraction term cancelling the $t\bar{t}$ contribution locally [21, 22]. There is on-going work on a consistent treatment as $WWb\bar{b}$ final state, including non-, single-, and double-resonant contributions, and quantum interference effects [23, 24].

ATLAS & CMS Diagram removal vs. diagram subtraction

2.4. Radiation

The amount of QCD radiation in an event affects top-quark reconstruction and selection efficiencies. Theory-inspired scale variations by factors of $1/2$ and 2 are found to be generous envelopes of jet multiplicity and gap fraction measurements in $t\bar{t}$ events performed by ATLAS [25, 26] and CMS [27, 28]. Final-state radiation inside resonance decays is tightly constrained by measurements of event shapes at LEP [29–32], and is validated by the ATLAS measurement of jet shapes in $t\bar{t}$ events [33].

ATLAS	Variation of renormalization scales in Alpgen+Pythia6
CMS	Variation of renormalization and factorization scales and ME-PS matching threshold in MadGraph+Pythia6

2.5. Momentum reshuffling and top-quark transverse momentum

Differential $t\bar{t}$ cross-section measurements indicate a softer transverse momentum (p_T) distribution than most predictions [34–37]. However, Powheg+Herwig6 simulation shows good agreement in top-quark p_T due to its momentum reshuffling scheme [38, 39]. In the $t\bar{t}$ NLO matrix-element used by Powheg, the real-radiation parton is generated with zero mass. Interfacing to a parton shower requires to assign virtuality to the additional parton, accomplished by rescaling the momenta of the top-quarks and the parton by a common factor. Other schemes are possible, like rescaling the momenta of the parton and the $t\bar{t}$ system, yielding a harder top-quark p_T , and are implemented in Herwig++. Pythia8 allows to compare a dipole-recoil and a global recoil scheme.

CMS	Reweight top-quark p_T to CMS measurement, assign full difference as uncertainty
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3. Soft QCD modeling

3.1. Hadronization model

After parton shower evolution down to a cutoff scale in the order of 1 GeV, hadrons are formed via Lund string [40] or cluster fragmentation [41,42] models. Similar tunings to e^+e^- data may lead to different predictions in top-quark events [43], where the detector response depends on momenta and types of stable particles. The comparison of the reference implementations in Pythia and Herwig is non-trivial due to further differences in parton shower, matching and underlying event, that may add up or compensate each other. A comparison of string and cluster fragmentation in Sherpa shows good agreement of parton→particle jet response and reconstructed top-quark and W-boson masses at particle level [44].

ATLAS	Powheg+Pythia6 vs. Powheg+Herwig6 in top-quark events, and Pythia6 vs. Herwig++ in (b) jet energy scale [45]
CMS	Pythia6 vs. Herwig++ as fully flavor-dependent jet energy scale uncertainty [46,47] Cross-checked by measurement of the b-jet energy scale in Z+b events [48], and Powheg+Pythia6 vs. MC@NLO/Powheg+Herwig6 comparison in top-quark events

3.2. b fragmentation

The fragmentation of bottom quarks influences b-tag efficiencies and b-jet energy response. The parameters of the fragmentation function are tuned to measurements of x_B in e^+e^- collisions [49–51], where $x_B = E_B/E_{beam}$ and B denotes the weakly decaying B hadron. Different tunings of the Bowler-Lund fragmentation function in Pythia are used to evaluate the uncertainty. The identification of charmed mesons inside b jets in $t\bar{t}$ events and the measurement of their momentum fractions establish a first step to validation of b fragmentation at the LHC [52].

ATLAS	Pythia6 AMBT1 vs. P11 vs. “Bowler modified” tunes in b jet energy scale
CMS	Pythia6 Z2* vs. Z2*rbLEP tunes in top-quark events

3.3. B -hadron decays

Measurements are affected by the uncertainty on B-hadron lifetime either directly by a lifetime-based observable or indirectly by b-tag efficiencies. As b-tag efficiencies are calibrated using data, no additional uncertainty is quoted for most measurements.

The branching ratio of B hadrons decaying via $B \rightarrow \ell\nu X$ has a direct impact on the fraction of undetected neutrinos inside b jets and thus on the b-jet response.

CMS	Envelope of PDG values for B^+ and B^0 semi-leptonic branching ratios [53]
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Pythia6 and Herwig6 contain reduced decay tables, and will be replaced by their successors Pythia8 and Herwig++ for the LHC Run 2. These contain improved decay tables, similar to those included in Sherpa and EvtGen.

3.4. Underlying event

A hard scattering process is accompanied by additional parton interactions of the protons, called the underlying event. Its description by event generators is tuned to particle spectra in minimum bias events. The origin of charged particles from the underlying event cannot be distinguished from the primary interaction vertex detected in experiment, so that their energy is added to clustered jets. Pile-up mitigation techniques based on particle densities may still compensate for variations of the underlying event activity and shape.

ATLAS	Pythia6 P11 vs. P11mpiHi, or P12 vs. P12mpiHi tunes
CMS	Pythia6 P11 vs. P11mpiHi and P11TeV tunes

3.5. Color reconnection

Color reconnection models allow non-perturbative changes in the color configuration of the event, typically reducing the total potential energy between QCD color charges [54]. This mechanism improves the description of charged particle $\langle p_T \rangle$ vs. N_{ch} in minimum-bias events, although the current models are not able to give a consistent tune to data in all p_T ranges. A new set of color reconnection models was recently implemented in Pythia8 [55].

ATLAS Pythia6 P11 vs. P11noCR, or P12 vs. P12loCR tunes
CMS Pythia6 P11 vs. P11noCR tunes

4. Summary and outlook

Simulated events are an important ingredient to LHC data analysis. The models need to be tuned to reference data in order to get accurate predictions for phase-space regions opening up at the LHC. A number of careful parameter variations in the simulation programs is performed to get a reliable estimate of the modeling uncertainties. There is on-going and successful work in harmonizing the different prescriptions used by ATLAS and CMS within the Top LHC working group, mainly driven by combination efforts.

For the LHC Run 2, new NLO+multileg generators are expected reduce the uncertainties on perturbative QCD [6, 56]. At the same time, the inclusion of weights for generator variations in both matrix element and parton shower has potential for efficient and precise estimation of the uncertainties, without dilution by limited statistical precision [57, 58].

Complementary analysis strategies are being followed to preserve ATLAS and CMS data for all practical purposes. New cross-section measurements quote results also in fiducial phase spaces that are closer to the detector acceptance [59]. The extrapolation from fiducial to inclusive cross sections will be possible using any improved calculation in the future, benefitting from reduced uncertainties. Definition of the top quark at particle level will reduce the modeling uncertainties on differential measurements [37, 60] and allow for generator comparison and tuning in the Rivet+Professor framework [61, 62].

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